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THE WORK OF THE BLACK SEA HYDROPHYSICAL STATION ON THE PHYSICS OF THE SEA

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/Figures referred to herein are appended./

In its 20 years of existence, the Black Sea Hydrophysical Station has always concentrated upon problems connected with the thermal regime of the sea, which governs the thermal state of water masses at various times of the year, and the entire dynamics of the sea (with the exception of tides).

The solar heat absorbed by sea water in the warm season plays an important role in the cold season, when the heat is given back to the atmosphere and creates considerably higher air temperatures over the sea than over continental regions. This difference in heating of air over sea and continent creates a sharp drop in atmospheric pressure between continent and sea in the winter. Consequently, winds are directed from continent to sea.

Until recently, books on oceanography paid very little attention to thermal phenomena in the sea, but now this tradition has been broken and a study of the thermal balance of the sea has been begun. Recording instruments continuously register the components of this balance, i.e., the amount of heat falling on unit surface of the sea from the sun and sky, and the amount of heat expended on evaporation of sea water and on heat exchange with the colder atmosphere (to determine these components, or elements, the station records wind speed and direction and the temperatures of the surface water and air over it). The resultant curve of input and output of heat per unit surface of the sea is constructed from the measured and calculated components. This curve makes it possible to determine the times when heating of the sea is replaced by cooling and vice-versa and to calculate the yearly behavior of the average temperature of the active layer of sea water, i.e., the layer in which marked temperature variations take place in a year's time.

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Cooling and heating connected with the activity of the wind in the shore belt are distinguished sharply against a background of yearly changes in sea water temperature. The station has been studying this problem for many years. It found that cooling of sea water is greatest when the wind is from right to left along the shoreline with respect to an observer looking seaward. When the wind is blowing in this direction, the warmer surface water is driven off into the open sea by the Coriolis force. The resulting loss of water is partially replenished by the influx of cold water in the layer near the bottom. Mobile equilibrium is established for a low sea when the amount of water entering from the bottom flow equals the amount of water driven off along the surface.

The cooling of waters in the coastal belt is closely related to local drops in sea level. This cooling in summer often reaches 10 or 15 degrees (the temperature falling from 20-25 degrees to 10-8 degrees centigrade).

When the wind is directed the other way, from left to right along the shoreline, cooling is replaced by heating. In this case, the surface waters are driven on to the shoreline, while the bottom (cold) water recedes from it. Mobile equilibrium is established when a certain level, high with respect to the sea level in calm weather, is attained. This means that the heating of waters in the coastal belt is connected with a local rise in sea level.

Thus, the study of the "driving off - driving on" phenomena is useful both for navigation in shallow-water regions, where underwater rocks may be dangerous during a low sea, and also for local fishing enterprises since fry react very sensitively to cooling of waters caused by the driving off of surface waters and hence move in whole schools to the shore.

The data of recording instruments and calculations made therefrom at the Black Sea Hydrophysical Station agreed with the observed behavior of water temperatures. The Black Sea experiments were therefore applied to other seas and the original instruments invented and constructed at the station were installed along the shores of these seas and on research ships. It is especially difficult to calculate temperatures in advance in polar seas since all processes are complicated by the fall freezing of sea water and the subsequent spring thawing office. The thermal shield afforded by the ice cover to the water is also of importance here. The Black Sea Hydrophysical Station's method of calculating the heat balance of the sea has been found useful in expeditions and at shore meteorological stations and observatories in forecasting the thermal state of the sea, especially in forecasting the times of freezing and opening of icy seas and large rivers which empty into icy seas.

Moreover, it was found that the heat extracted from waters by very cold air plays a decisive role in the thermal regime of the northern seas. The heat taken from sea water, in turn, becomes still more important later when it is transferred by air masses to the continent, thus moderating the climate of continents. This moderating influence of the ocean and even of inland seas has long been recognized. However, a quantitative theory of the moderating influence of the ocean and inland seas upon the climate of continents and in particular upon the climate of the USSR has been devised only recently in the USSR. We have been able to calculate the amount of heat that is transferred from ocean to continent per unit length of shoreline for any month in the cold season and the amount in the reverse direction for the warm season.

We have also been able to calculate the amount of heat which "oceanic" thermal currents return to the atmosphere over the USSR.

In Figure 1, a diagram for Leningrad Oblast is reproduced for illustration. The months are on the abscissa and the amount of heat per month per square centimeter of continental surface is on the ordinate. The lower curve shows the amount of heat liberated for any month within an air column resting on one square centimeter of land due to the air column's being heated by a thermal current from the ocean. The segments of the vertical straight lines between the lower curve and the upper curve show how much heat is liberated in this air column because of its heating by the thermal current which flows in the atmosphere from warm to cold countries (along meridians). The upper line calculated from our theory represents the total heating of air over the continent under the action of both currents. For comparison, we have plotted on the same diagram the points obtained at the Pavlovsk Aerological Institute (of the Main Geophysics Observatory) from data of direct observations and subsequent calculation of the heat balance of the atmosphere; these express the "deficiency" of heat in the atmosphere which is needed to cover thermal currents in the atmosphere. As seen from Figure 1, our theoretical curve borders very closely upon the empirical points.

The term heat "deficiency" has real physical meaning, e.g., the heat expended by the atmosphere through radiation into interplanetary space in Leningrad Oblast is no way covered in winter by the insignificant amount of heat which is obtained directly from the sun.

The picture becomes even clearer in the north. For most of the year, the main amount of heat creating the climate is not furnished directly by the sun, but by horizontally directed thermal currents in the atmosphere, i.e., from the ocean to the continent and from warm countries along meridians.

After analyzing this problem and obtaining confirmation of theoretical calculations by direct observations, the Black Sea Hydrophysical Station began work which would (also from the quantitative side) characterize the influence of thermal contradictions between sea and continent upon the important elements of climate and weather both over the sea itself and over the continent. To simplify calculations, the simplest case, i.e., that of a circular sea enclosed by a continent was studied first. The results are shown in Figure 2, where the sea in cross section is shown by a horizontal thick black band, and the continent, by the hatched portion.

The curve tau shows the distribution of air temperatures over sea and continent. It closely approximates the distribution actually observed over inland seas of the USSR in the winter.

The curve in the middle of the diagram shows the amount of heat taken by the air from a circular band of the sea for various distances from the center and then delivered to corresponding circular bands over the continent.

The bottom of the diagram contains the curves v and w, which express the distribution of prevailing air currents in winter over sea and continent. Curve v in arbitrary scale gives the components of wind velocities along the radius of the sea, and w gives the velocities of currents ascending over the sea and descending over the continent. The diagram shows that the prevailing winter winds (of monsoon origin) must attain their greatest force in the coastal belt, which condition actually prevails. The monsoon currents are weakened in the middle of the sea and far from it over the continent. The ascending currents, even though they do not attain great velocities, are important since they carry crystals of sea salts high into the air. These salt crystals serve as condensation nuclei for water vapor around which clouds form to be borne into the depths of the continent by horizontal monsoon currents. At present, we are making a systematic study of salts carried out from the sea to the continent to help determine the origin of precipitation in European USSR.

Figure 3, also constructed from our theory, shows how the size of the sea influences the climatic characteristics shown in Figure 2. The radius of the sea in thousands of kilometers is placed along the abscissa. Curve 1 shows how the air temperature in the middle of the sea increases with the radius of the sea. The temperature which air at the same latitude would have if there were no oceans on the earth was taken as an arbitrary zero. The temperature increase which would arise if the earth were covered by ocean was taken as the unit of temperature increase.

Curve 2 shows the temperature increase on the coast of a sea of arbitrary radius with the same arbitrary quantities as were used in Curve 1.

The theory permits the solution of a similar problem for the case of a circular island of arbitrary size enclosed by an ocean. Curve 3 shows how the temperature drops in the center of this island when its radius increases. Curve 4 gives a similar law for the drop of air temperatures over the shore of the island.

In addition to air temperatures, we also determined the velocities of winds of monsoon origin which must arise over the shore of a circular sea enclosed by a continent (curve 5) or over the coast of a circular island enclosed by an ocean (curve 6). The velocity which would arise over a shore if the earth were half covered by ocean and half by continent was taken as a unit of wind velocity.

All calculations were made for the simplest form of a sea or inland, namely a circle. Later, it proved possible to extend these calculations to more complex shoreline forms. Figure 4 shows the sharpening of a monsoon wind field at the ends of an oblong sea of elliptical form. Figure 5 shows the still greater sharpening of a wind field against a pointed v-shaped cape. The greater the number of curves on the diagrams, then the closer the neighboring curves, the greater the intensity of the monsoon field, and the greater the wind velocity created by the corresponding drop in atmospheric pressure. Figure 5 also shows the weakening of the field over the surface of a bay which is wedged into a continent. It is interesting to note that a similar sharpening of contradictions between sea and land arises in the case of an elliptical island surrounded by an ocean (corresponding to Figure 4) and in the case of a pointed cape cutting into an ocean (corresponding to Figure 5). Direct observations confirm the theory, e.g., the violent storms characteristic of the ocean regions around Cape Horn and the Cape of Good Hope, and even around small capes such as Kanin Nos in the north and Cape Tarkhankut and Cape Sarych on the Black Sea. The sharp ends of Novaya Zemlya (Cape Zhelaniye, for example) create the same local intensification of wind activity as the sharp ends of Lake Baykal, which fact agrees completely with our theory.

These studies can give only a fairly satisfactory picture of the climate, since actually there are no air currents of constant velocity and no thermal currents of constant depth. Very often in nature, there arise spontaneous oscillations of various quantities, which are studied intensively by present-day theoretical physics. From our standpoint, such spontaneous oscillations of air temperature and atmospheric pressure unavoidably arise in air currents carrying heat from ocean to continent and in air currents of other origins existing in the atmosphere. We understand these oscillations of atmospheric conditions and thermal currents as a change in weather. As with any spontaneous oscillations, they must receive energy from some source, in this case, the sun. In the winter the solar energy obtained is transferred by air from ocean (heater) to continents (coolers) and from tropical belt (heater) to polar countries (coolers). In the summer, the role of tropical and polar countries is unchanged, but the ocean and continents exchange places, i.e., the ocean cools and the continents heat the atmosphere.

As in certain other cases, air temperature oscillations and related variations in atmospheric pressure take place in the form of waves, moreover, in the form of so-called standing waves. Heating and its concomitant low pressure simultaneously encompass an entire region lying within a certain closed curve. Outside its boundaries, cooling and its concomitant high pressure prevails. After a definite time interval, i.e., an alternation or half-cycle of oscillations, the region which was first heated becomes cooled and the region first cooled becomes heated. The changes in atmospheric pressure correspondingly alter sign, high pressure prevailing over the first region and low over the second.

The unusual freezes in January 1940 are a good illustration of our theory. As seen on the diagram (Figure 6), they encompassed first the Ukraine and even the Crimea; the broken curve corresponding to these parts of the country dropped sharply around 10 January. At the same time, there was a thaw in the north, as shown by the solid curve in the same figure. After an alternation, approximately a week in this case, a thaw set in the south, while the north was struck by freezes of around 45 degrees below zero. Fortunately, such powerful standing waves are seldom observed. On the other hand, more subtle phenomena, but nonetheless very damaging to agriculture, are observed very frequently. For example, the May cold spells, which cover great regions, are observed every year during the transition of the winter monsoon season to the summer season. As in the preceding case, cooling of these regions is preceded by abnormal warming, which sometimes passes unnoticed since it is natural to expect warming in the spring. Around the heated region lie cooled regions and in the following phase heated regions will lie around the cooled region.

Despite its present imperfections, the theory of temperature and pressure seiches may be of great value for forecasting periods of abrupt cooling. As a rule, these periods will follow any abnormal warming.

The winter season is important to the study of storm waves in the sea in the same way that the spring transition is important to the study of powerful air-temperature oscillations and their concomitant pressure variations.

Perennial observations on the behavior of storm waves close to the shoreline and resulting theoretical studies made it possible to establish the laws of wave propagation for variable depth. A very simple graph was drawn up to aid in determining the direction of approaching waves near shore in connection with various requirements for the protection of port construction and shore reinforcement from destructive waves.

Results of theoretical calculations agreed with control observations in which specially designed and constructed wave-measuring instruments were used.

One of these wave-measuring instruments has now been accepted for series production in order to equip the entire network of marine hydrometeorological stations and marine observatories. It can be used to measure from shore the height and length of waves and their speed and direction at considerable distances out to sea. The same instrument can be used to measure the speed of currents in the coastal zone in weather so stormy that it is impossible to send out a launch or work with a ship close to shore. To carry out these measurements, a rigidly mounted (at a definite angle to the horizontal) converted mortar gun is set up on shore. Wooden balls are projected about 250 meters out to sea by the mortar and, after falling into the water, release a semispherical metallic cup. The cup is connected with the ball by a hempen cord and is designed so that the ball will move along the surface of the sea under the action of the current alone, and not under the action of the wind. Tracking the ball by means of an instrument, the observer can plot its successive positions on paper and thus determine the current speed at any time and the dependence of this speed upon wind activity.

The bottom currents must also be known to determine fully the influence of wind upon shore currents. These currents are registered at the Black Sea Hydrophysical Station by special recording instruments which note both the current speed along the shore line and the speed in a direction perpendicular to the shore.

Crashing waves (together with bottom currents) very frequently destroy the shore, thus heavily damaging shore constructions, causing landslides, and even menacing buildings slightly removed from shore. It would be beneficial to direct the energy of waves along another bed to force them to do useful work.

One method of solving this problem was proposed by one of our workers, who designed a unique wave ram. Crashing into his construction, the waves produce high crests and thus raise a considerable amount of water into a canal. From the canal, the water can flow through ordinary turbines connected to electric generators.

Unfortunately, similar progress has not been observed in using this energy to move ships directly, but some success has been attained in combatting the harmful action of waves against ships. It has long been known that the most dangerous, i.e., foamy and very sharp, wave crests, can be modified by dropping fine layers of oily substances on the surface of the sea. The most diverse explanations of this remarkable phenomenon have been advanced in literature, but are usually a long way from the truth. Simple experiments have enabled us to establish the actual cause for the calming action of oil substances. The mechanism of calming can be represented as follows:

Oils have the ability to spread very rapidly along the surface of water in a fine film only two or three molecules thick (depending upon the distance to the boundary of the section covered by the substance; close to the boundary, the film thins down to one molecule). When the crest of a sea wave passes under the film, the corresponding water surface contracts, thus forcing several molecules of the oil to move downwards into deeper rows of molecules. Conversely, when the trough of a wave passes beneath the film, the corresponding water surface expands and thus the "drowned" oil molecules can again rise to the top.

The size of the oil molecules is very great in comparison with the water molecules, while their form is extremely complex and branched. Both these factors create very great internal friction and very high viscosity in the surface film. Consequently, under constant displacement of molecules of such a substance, first downwards and then upwards, energy must necessarily be expended to overcome viscosity in the film. The shorter the period of the waves, the greater the effect of this phenomenon. Quantitative studies made here showed that the amount of energy absorbed by viscous forces in short steep waves considerably exceeds the energy supplied by the wind. Consequently, in the uneven struggle, the energy of these waves must quickly by exhausted.

These same measurements made it possible to select those oil substances which provide the best calming action. The amount of oil needed to calm waves is very small, e.g., one glass quickly spreads to a surface of about 40,000 square meters.

An interesting phenomenon has been discovered in the field of "marine acoustics". We discovered that a high wind passing over sea waves creates in the atmosphere elastic oscillations which are propagated in all directions with the speed of sound waves. This "voice of the sea", as we have named it, is approximately an octave lower than the lowest note of a double-bass, and thus cannot be heard by the ear as sound. However, the ear drum and the inner ear receive the effect of the "voice of the sea" in another way, namely: if a thin-walled rubber sphere filled with hydrogen is brought up to the ear, a sharp pain will be felt in the ear, as if caused by pressure on the ear drum. It turned out that this feeling of pain, with which many practical aerologists who have launched pilot balloons are familiar, is caused by strong oscillations of the pilot balloon envelope which fall into resonance with the waves of the "voice of the sea." Hydrogen here has the role of a foreign medium differing greatly in its acoustic properties from air. That is why the infrasonic waves falling on the pilot balloon cause oscillations of its envelope with a frequency of about 10 vibrations per second. If the balloon were filled with air, the infrasonic waves would pass freely through it without disturbing its rest state.

A rubber balloon filled with hydrogen is of course a poor instrument for detecting signals coming from a region of sea covered by a storm. Diffusion transfer between the inner and outer space takes place continuously through

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the envelope, resulting in the rapid replacement of hydrogen by a volatile mixture within the envelope and making the balloon dangerous to store aboard ship or even in a laboratory. We have therefore initiated studies on other instruments capable of responding to remote storm signals transmitted by the sea. Unfortunately, great difficulties have been encountered, e.g., these signals are clearly detected only when a calm prevails at the observation point since local winds introduce such strong disturbances that the influence of distant infrasonic waves is lost against their background. However, there is reason to believe that in the near future we will successfully screen out these noises and thus obtain real automatic storm warnings from the sea itself.

The Black Sea Hydrophysical Station has also conducted various studies in the field of technical physics of the sea. One of these is the problem of utilizing the energy of waves. Another important branch was initiated by the classical works of Academician A. N. Krylov, who first created the principles underlying the theory of ships. The studies of our collaborators have concentrated on the reasons why some ships are tossed violently on a wave crest while others are left almost undisturbed by the same wave. These works owe their successful completion (including numerical calculations) to a method which permits the complete solution of the very complex problem of oscillations of a ship on a wave. This problem cannot be solved by direct classical methods. The substance of this method follows: if a certain falling sphere collides with another sphere floating in water (half submerged), the velocity attained by the latter can be calculated by an elementary formula describing the impact of spheres if one change is made, namely, another slightly higher mass must be substituted in the elementary formula instead of the mass of the floating sphere. N. Ye. Zhukovskiy showed that this mass is equal to the mass of the sphere itself plus a supplementary, so-called "added" mass, which owes its origin to water which is partially carried away by the sphere from the very beginning of its forced motion. We considered it natural to develop Zhukovskiy's study further and to extend it to the case of a floating body of arbitrary form which oscillates in the vertical direction. Such oscillations around a floating body create ring-shaped waves which are propagated from "a hydrodynamic vibrator", namely the body under study. The vibrator expends considerable energy in emitting these waves, and thus its oscillations are continuously damped. The energy carried away by waves is presumably the same energy originally connected with the added mass of water carried away by the vibrator. But the added mass characteristic of various forms for the floating body can be calculated from simple relationships, and in other cases may be determined from experiments on a ship model or the ship itself. Consequently, we can calculate the energy carried away by waves for each period of oscillation of the floating body, starting from our two propositions above. On the other hand, if we know the energy carried away and the energy possessed by the vibrator for various amplitudes of oscillations, we can easily determine how rapidly the amplitude of these oscillations will decrease. In particular, for oscillations of a floating sphere, each successive amplitude will be only 2/3 that of the preceding one; for a half-submerged cylinder it will be 1/2. Naturally, it is assumed here that the energy is expended in no other way than waves emitted around the vibrator. Actually, a correction must sometimes be introduced for the energy absorbed by friction around the water and for the energy expended on eddy formation in the surrounding water.

Taking these corrections into consideration, we can easily compare our theoretical calculations with the results of direct experiments on models of various floating bodies, on ship models, and on the ships themselves under natural conditions. In all cases, for the time being, only vertical oscillations of the center of gravity, and not rolling and heaving were considered. Checking of the theory on many examples has given good results, thus confirming both of our original assumptions.

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Cases of rolling and heaving are slightly more complex. Even here, however, our simple method permitted complete solution of interesting practical problems. In particular, it was possible to calculate (for a given form of ship) the probable amplitudes of tossing of the ship on a given wave and to determine the steps which must be taken in designing new ships to avoid great amplitudes.

As might be expected, the amplitudes of tossing on a wave are inversely proportional to the amount of damping of the natural oscillations of a ship displaced from its state of equilibrium on perfectly calm water, i.e., the greater the damping, the less the tossing. In turn, quite definite practical methods were found to increase the damping of natural oscillations of a ship. These methods should aim at ensuring that a ship displaced from a state of equilibrium by some force will have the least energy store for some given heeling angle. Naturally, this aim can be pursued only until the measures taken begin to endanger the so-called "stiffness" of a ship, necessary for safe navigation.

The Black Sea Hydrophysical Station expanded continuously in the Soviet period and by 1941 possessed several laboratory buildings, a well-equipped instrument-building shop, residential dwellings in the village of Katsiveli, its own small but well-equipped survey ship, and its own power station. These were, for the most part, destroyed in World War II, but reconstruction, initiated one week after the liberation of the Crimea, progressed rapidly. The laboratory buildings were expanded; a new laboratory was constructed from a design proposed by Academician A. V. Shchusev; a large experimental storm basin was built. By government decree, the Black Sea Hydrophysical Station and the Moscow Marine Laboratory were reorganized into the Marine Hydrophysical Institute of the Academy of Sciences USSR, consisting of the Black Sea and Moscow departments. For the latter, the Moscow Council of Workers' Deputies presented a fine building not far from Moscow in Lyublino. In it and around it, on the shore of a reservoir, experimental installations are being built for work on models which do not require direct sea conditions so much as proximity to the capital with its libraries and scientific and official institutions.

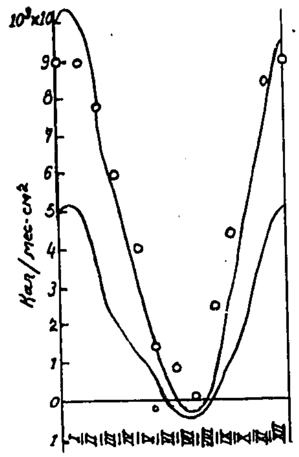

Figure 1. The Heat Brought In By Currents From the Ocean and From the South

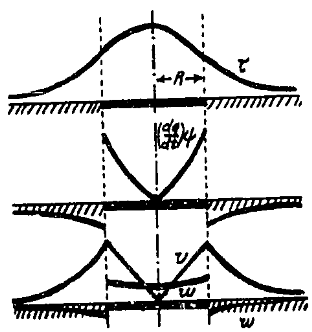

Figure 2. A Monsoon Field Over the Sea and Over the Continent

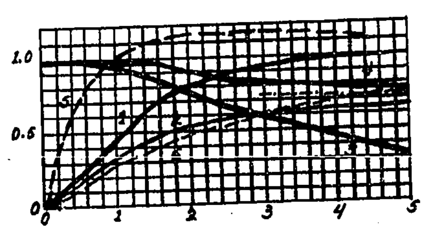

Figure 3. Characteristics of a Monsoon Field for Various Sizes of a Sea and Various Sizes of an Island in the Ocean

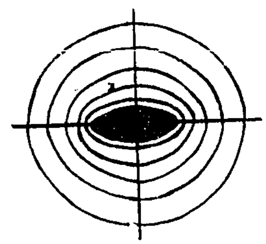

Figure 4. A Monsoon Field Around an Elliptical Sea

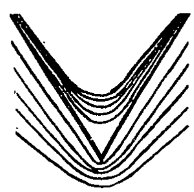

Figure 5. The Monsoon Field of a Cape and a Bay

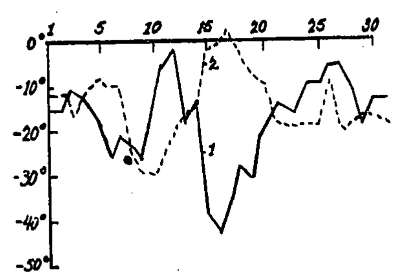

Figure 6. Temperature Oscillations

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